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# Account for the contribution of higher vibration modes under seismic resistance estimation of system with elastomeric supports by nonlinear static method

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**Abstract.** The article presents higher vibration modes accounting method to evaluate system seismic resistance by nonlinear static method. As part of the study, in order to verify the proposed method for finding the inertial forces modified system series of dynamic and static calculations was performed. Proposed inertial forces modified system can be applied for seismic resistance estimation of system with elastomeric supports. The results difference varies within 12%.

## 1. Introduction

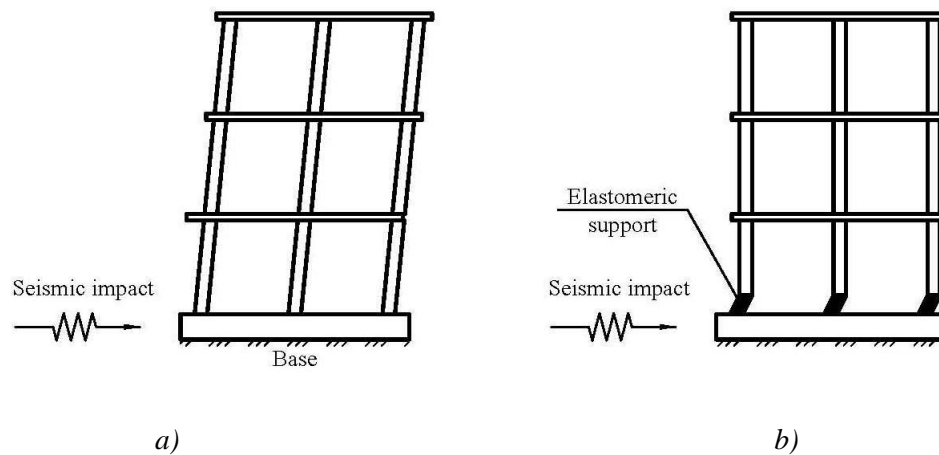
Annually about 300 thousands earthquake occur in the world. The epicenter of most of them is located far from settlements, and the magnitude of exposure is small enough. However, some earthquakes have disastrous effects on entire cities destroying them and causing enormous economic damage. Thus, the seismic resistance increase is one of the actual issues during construction in seismically hazardous areas.

Usually seismic resistance is achieved by structural element stiffness increasing (passive seismic protection), that leads to inertial loads rise. Thus, this solution is not always rational and economically feasible.

In the 60s of the twentieth century an alternative way for earthquake resistance was proposed - seismic isolation (active seismic protection). The term "seismic isolation" means a inertial forces decrease caused by seismic impact, using special elements to reduce the inertial loads on the system. Figure 1

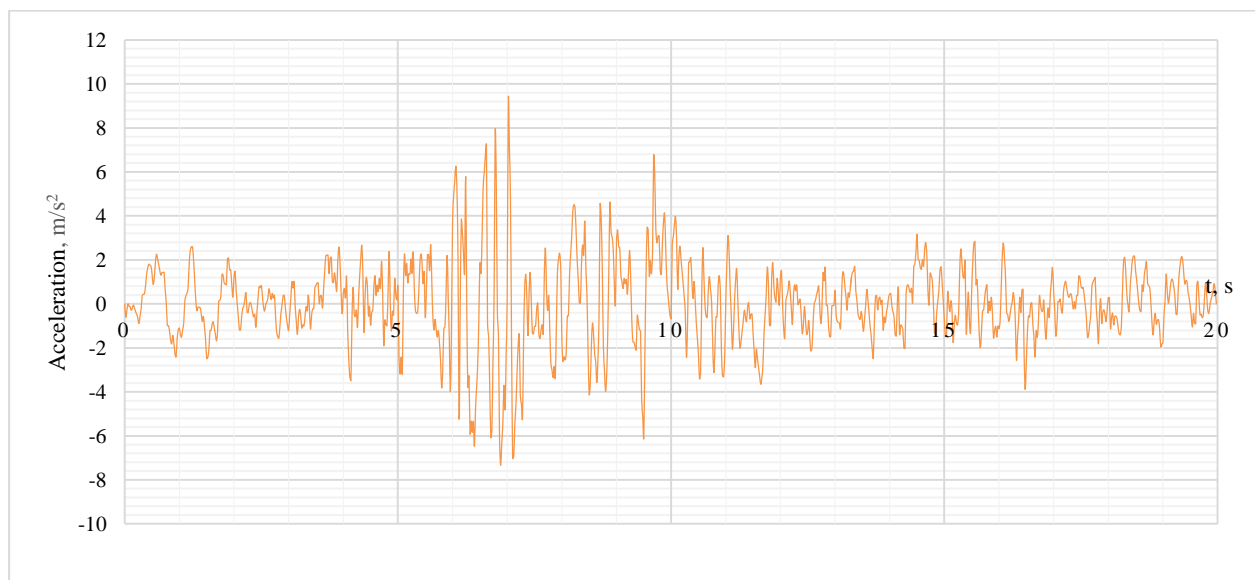


shows the deformation of the building scheme without seismic isolation and with its application. Due to greater compliance in the lower part of the system, horizontal displacements generally increase with decreasing mass acceleration.



**Figure 1.** Deformed building scheme: *a) – building without seismic isolation;*  
*b) – earthquake-proof building*

According to [1] seismic resistance estimation is performed using the direct dynamic method by integrating the equations of motion in the time domain using a ground accelerations instrumental records set or synthesized accelerograms (Figure 2). Such calculations require a large time resource, sophisticated software and special design skills.



**Figure 2.** Horizontal component accelerogram, Iran, 1978

A dynamic method alternative is the nonlinear static method - Pushover analysis. The structure under calculation is subjected to monotonically increasing horizontal forces. According to [2], [3] the inertial forces system must correspond to the forces distribution of one of the possible natural vibration modes. This limitation does not allow to provide an accurate seismic resistance estimation.

This article considers a three-mass dynamic model with elastomeric support. Method of accounting for higher vibration forms under Pushover analysis was proposed. Seismic resistance estimation were performed using the direct dynamic method and the multimodal nonlinear static method.

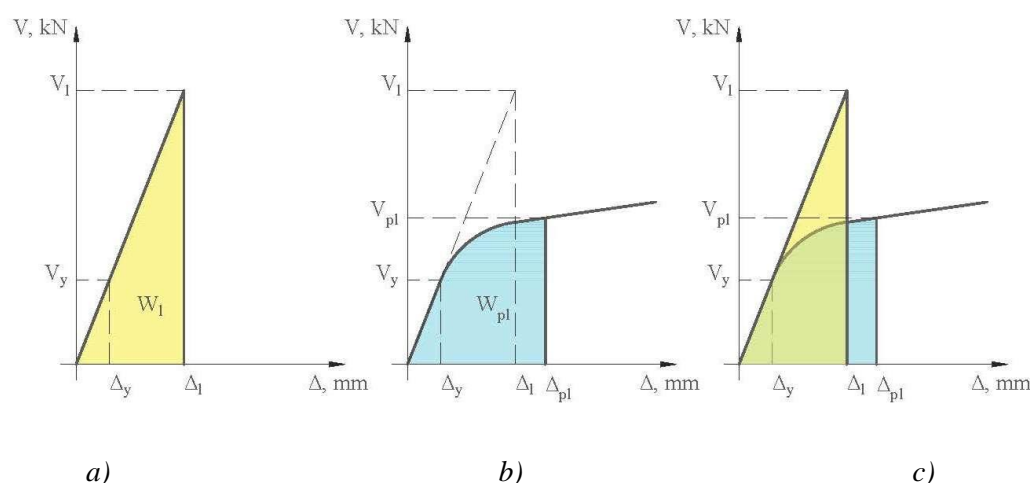
## 2. Higher vibrations forms accounting method

To determine the response of the system, taking into account the influence of higher vibration modes, we consider the following method with modified system of inertial forces.

The inertial forces modified system is the system based on the SRSS-method, in which the top displacement of considered model will correspond to the total displacements obtained by response spectrum analysis.

According to [6] to destroy a material, no matter what the load is applied, it is necessary to expend the same amount of energy. Thus, the linear system deformation energy with a inertial forces modified system is identical to the system deformation energy, taking into account plastic deformations.

The seismic resistance evaluation next stage is to plot the capacity curve “Force at the base  $V_b$  - Displacement of the system top  $\Delta$ ” based on nonlinear static calculation for the system with one degree of freedom under the modified inertial forces system – capacity curve.



**Figure 3.** System energy intensity under elastic and elastoplastic behavior: a) *elastic behavior*; b) *elastoplastic behavior*; c) *energy equality under elastic and elastoplastic behavior*

According to energy equality under elastic and elastoplastic behavior it is necessary to find the area under the capacity curve, which is equal to pre-determined energy intensity. The point on the  $\Delta$ -axis providing equal areas is the characteristic seismic resistance estimation point, on the basis of which it is possible to determine interstorey drifts, elements internal forces and plastic hinges and fracture sites.

## 3. Problem statement and method testing

Three masses 9-meters high column was selected as representative case study to carry out the performance-based seismic methods evaluation.

As a construction material structural steel was chosen. Stress-strain diagram is shown on Fig. 5. To describe the non-linear behavior of the system elements the model of Bilinear Kinematic Hardening has been adopted. The diagrams of steel deformation under tension and compression are the same. The yield surface is described by the Von-Mises criterion and is a cylinder whose axis coincides with the axis of hydrostatic compression in the axes of the main stresses. Damping parameters were calculated based on 1<sup>st</sup> and 3<sup>rd</sup> natural vibration frequency. Dynamic model characteristics are shown in Table 1. The seismic excitation used for nonlinear time history and pushover evaluations is defined by a set of three strong ground motions:

1. Iran, 1978 г. (Erthq. 1);
2. El Centro, USA (California), 1979 г. (Erthq. 2);
3. Duzce, Turkey, 1999 г. (Erthq. 3).

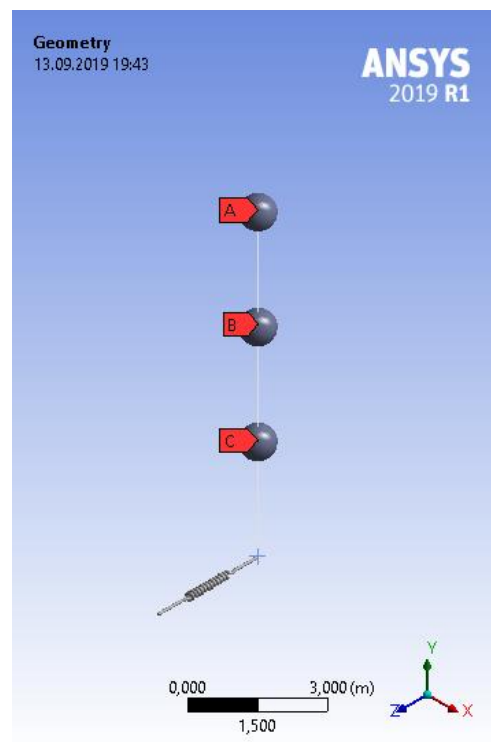
Accelerogram records were taken from [8].

To calculate the forces system for a given system during the seismic evaluation by the multimodal nonlinear static method, the initial data are the inertial forces of the first three vibration modes.

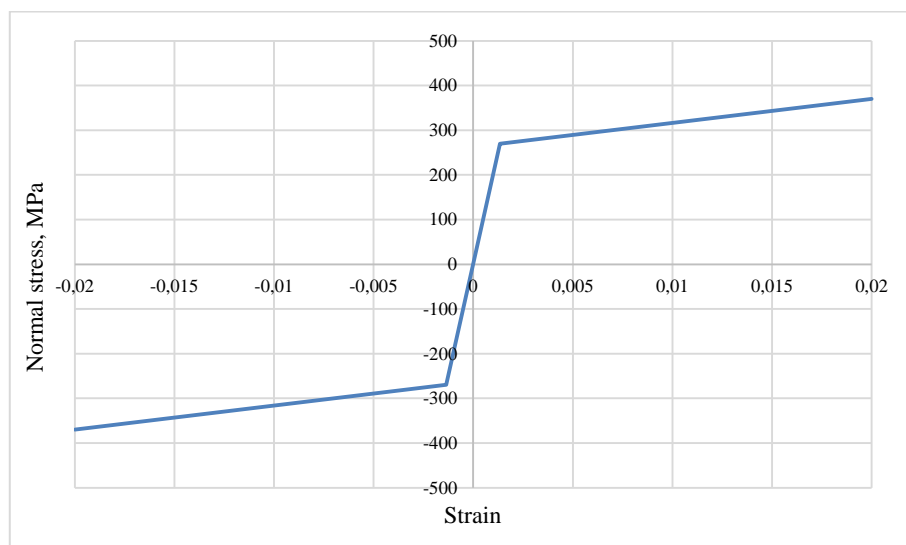
The inertial forces distribution and the forces resulting system for seismic impact Iran, 1978 (Erthq1) are obtained by response spectrum analysis.

**Table 1.** Dynamic model characteristics

№	Nomination	Value		
		Erthq. 1	Erthq. 2	Erthq. 3
1	Cross-section, <i>mm</i>	<i>I-beam 300(h)x200(b)x15(b<sub>f</sub>)x8(b<sub>w</sub>)</i>		
2	Height, <i>mm</i>	9000		
3	Young modulus, <i>Pa</i>	$2e^{11}$		
4	Yield point, <i>MPa</i>	270		
5	Tangential modulus, <i>MPa</i>	$5.361e^3$		
6	Masses $m_a = m_b = m_c$ , <i>kg</i>	4300	9500	8000
7	1 <sup>st</sup> natural vibration frequency $f_1$ , <i>Hz</i>	0.677	0.4587	0.4993
8	2 <sup>nd</sup> natural vibration frequency $f_2$ , <i>Hz</i>	2.9099	1.9826	2.1562
9	3 <sup>rd</sup> natural vibration frequency $f_3$ , <i>Hz</i>	8.6516	5.9096	6.4245



**Figure 4.** Dynamic model general view



**Figure 5.** Stress-strain diagram of steel

To calculate the inertial force reduction coefficient, a linear static analysis was performed. The resulting coefficient value and the system's energy consumption is presented in Table 2.

The next step in seismic evaluation is to perform a non-linear static calculation under the action of a inertial forces modified system. Then the capacity curve is plotted in the coordinates of the "shearing force at the base — the top displacement of the system".

The characteristic point search is iterative: it is necessary to find such a point on the capacity curve so that the figure formed under the graph area corresponds to the target system energy consumption.

The results obtained for seismic impacts Erthq1..3 are summarized in Table 2.

**Table 2.** The results obtained by the multimodal nonlinear static method

№	Nomination	Value		
		Erthq.1	Erthq.2	Erthq.3
1	Inertial force at the upper node, <i>kg</i>	3573.4	3633.4	4324.73
2	Inertial force at the middle node, <i>kg</i>	3029.4	3127.0	3936.68
3	Inertial force at the lower node, <i>kg</i>	4928.7	5105.5	6793.54
4	Elastomeric support inertial force, <i>kg</i>	96.58	46.19	72.92
5	Upper node maximum horizontal displacement obtained by response spectrum analysis, <i>mm</i>	256.60	250.77	230.02
6	Upper node maximum horizontal displacement obtained by static analysis with inertial forces modified system, <i>mm</i>	497.47	509.09	625.86
7	Reduction factor $\alpha$	0.5158	0.4926	0.3675
8	Maximum system termination lateral force under the inertial forces reduced system action, <i>kN</i>	58.18	57.32	54.38
9	Potential strain energy / Energy consumption, <i>J</i>	377.311	359.36	312.74
10	Upper node maximum horizontal displacement obtained by multimodal pushover analysis, <i>mm</i>	283.5 254.42	274.46 245.98	249.5 220.9

№	Nomination	Value		
		Erthq.1	Erthq.2	Erthq.3
11	Middle node maximum horizontal displacement obtained by multimodal pushover analysis, <i>mm</i>	181.68 152.60	165.22 136.74	150.3 121.7
12	Lower node maximum horizontal displacement obtained by multimodal pushover analysis, <i>mm</i>	81.01 51.93	73.28 44.79	67.1 38.5
13	Maximum bending moment near the anchorage obtained by multimodal pushover analysis, <i>kNm</i>	285.14	278.3	269.06
14	Maximum shear force near the anchorage obtained by multimodal pushover analysis, <i>kN</i>	50.48	49.44	48.84

#### 4. Results

To estimate the responses error obtained by the multimodal nonlinear static method, it is necessary to compare the results with the responses obtained by the time history the direct dynamic method using the acceleration records Erthq1-3 [8].

To assess the quality of the obtained data, the statistical processing was performed:

- The horizontal displacements average error is 5.16%; standard deviation - 9.55%;
- The bending moment average error is 3.59%; standard deviation -3.58%;
- The shear force average error is 12.57%; standard deviation -5.18%.

**Table 3.** Multimodal nonlinear static method error estimation under the seismic impact Iran, 1978 r. (Erthq1)

Parameter		Time history dynamic method	Multimodal nonlinear static method	Error, %
Horizontal displacement, <i>mm</i>	Upper node	-256.90	-254.42	-0.96
	Middle node	-136.00	-152.60	+10.88
	Lower node	-40.10	-51.93	+22.78
Maximum bending moment near the anchorage, <i>kNm</i>		263.10	285.14	+7.73
Maximum shear force near the anchorage, <i>kN</i>		44.74	50.48	+11.37

**Table 4.** Multimodal nonlinear static method error estimation under the seismic impact El Centro, USA (California) (Erthq2)

Parameter		Time history dynamic method	Multimodal nonlinear static method	Error, %
Horizontal displacement, <i>mm</i>	Upper node	-260.56	-245.98	-5.59
	Middle node	-139.97	-136.74	-2.31
	Lower node	-42.59	-44.79	+4.9

Maximum bending moment near the anchorage, $kN\cdot m$	267.00	278.3	+4.06
Maximum shear force near the anchorage, $kN$	39.83	49.44	+19.44

**Table 5.** Multimodal nonlinear static method error estimation under the seismic impact Duzce, Turkey, 1999 r. (Erthq. 3)

Parameter		Time history dynamic method	Multimodal nonlinear static method	Error, %
Horizontal displacement, $mm$	Upper node	-261.08	-250.9	-3.89
	Middle node	-143.04	-151.7	+5.7
	Lower node	-46.37	-54.5	+14.9
Maximum bending moment near the anchorage, $kN\cdot m$		271.78	269.06	-1.00
Maximum shear force near the anchorage, $kN$		45.44	48.84	+6.9

## 5. Conclusions

Multimodal nonlinear static method was proposed to take into account the higher vibration modes influence under seismic evaluation.

According to the calculation results, it can be concluded that the proposed methodology calculation is useful.

The developed method allows to evaluate the seismic resistance of structures with elastomeric supports, besides summing inertial forces method is most likely to determine the total inertial load. The results difference obtained by the time history dynamic method compared to results based on the multimodal nonlinear static method is about 12%.

New term "System energy intensity" in Pushover analysis theory can significantly simplify the characteristic point search method.

Comparing two methods for seismic analysis its clear seems the time-history analysis is relatively more time consuming and costly than multimodal nonlinear static method.

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